Conceptual Design and Comparative Study of Strut-Braced Wing and Twin-Fuselage Aircraft Configurations with Ultra-High Aspect Ratio Wings

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Sustainable and fuel-efficient next-generation air transportation demands a step change in aircraft performance. The ultra-high aspect ratio wings (UHARW) configuration is one key enabling strategy for improving aircraft aerodynamic efficiency and reducing fuel consumption and emissions. Unconventional aircraft configurations and novel airframe technologies are required to address the large bending moment, and shear stresses in the UHARW structure. This paper considers two promising unconventional configurations suitable for adopting UHARW design, including strut-braced-wing (SBW) and twin-fuselage (TF), equipped with novel airframe technologies, i.e., active flow control, active load alleviation, and novel airframe structures and materials. Three typical missions, including short-range (SR), medium-range (MR), and long-range (LR), are considered for aircraft design. A conceptual design and performance analysis framework for the SBW and TF configurations with novel airframe technologies is developed in this paper by integrating and improving several methods and tools. According to the mission profile and top-level requirements proposed for each mission, an SBW and a TF configuration are designed for each class of aircraft. A comparative study is carried out to determine the best-in-class configuration of the corresponding mission. The results showed that the TF configuration has a better wing weight reduction effect than the SBW configuration, and the MR-TF and LR-TF aircraft have lower takeoff weight and fuel weight than the SBW aircraft for the same mission. However, due to the adjustment of the dimensions for the cabin arrangement of the SR-TF aircraft, the SBW configuration outperforms the TF configuration in this mission.

I. Nomenclature

ICAO	=	international civil aviation organization
MTOW	=	maximum takeoff weight
R & D	=	research and development

II. Introduction

Stringent sustainability goals for the next generation of commercial transport aircraft have been put forward by NASA [1] and European Commission [2] in recent years, including significant CO2, NOx, and noise reductions. In particular, in recovering the aerospace industry, which has been hit seriously by the unexpected COVID-19 pandemic, regaining its competitiveness, and addressing future climate goals, an unprecedented revolution in air transportation is required. Therefore, a step-change in aircraft performance is needed, for which the advancement in ultra-high aspect ratio wings (UHARW) configurations become one of the keys. In recent years, some efforts have been put forward to explore the

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benefits and potentials of UHARW, such as wingtip coupling, strut-braced wings, multi-fuselage, folding wings, etc. [3-5].

The wing bending moment of the UHARW is drastically larger than that of the conventional wings. Therefore, the wing structural weight penalty will be huge if there are no additional designs or structures to assist the UHARW. The strut of the Strut-Braced Wing (SBW) aircraft could reduce the maximum bending moment in the wing structure by significant amounts, typically up to 50%, which will significantly reduce the wing weight, thereby increasing the wingspan and reducing the wing thickness and sweep [6]. For this reason, most of the current research on UHARW is focus on the SBW configuration [6, 7]. For example, the Subsonic Ultra Green Aircraft Research (SUGAR) team consisted of NASA, Boeing, and the Georgia Institute of Technology has comprehensively studied the SBW technology for the next-generation mid-range (MR) commercial transport aircraft [8].

Another promising concept for the UHARW is the twin/multi-fuselage configuration [5]. This aircraft configuration targets reducing aircraft weight by two effects. The fuselages with their payload are located away from the aircraft centerline, reducing the wing bending moment. Moreover, Twin-Fuselage (TF) aircraft use the fuselage volume better than the single wide-body configuration for integrating passengers on large aircraft, thereby reducing fuselage weight by up to 40% [9]. The TF concept has already been realized in large aircraft and Unmanned Aerial Vehicles (UAVs), such as a TF UAV [10], a general aircraft HY4 [11], WhiteKnightTwo [12], etc. However, this concept still has not been investigated in detail for transport passenger aircraft, probably due to airport infrastructure constraints (e.g., runway width and terminal access).

There have been numerous projects and research on UHARW aircraft, including the SBW configuration, the TF configuration, etc. However, current research on UHARW aircraft configurations and missions is not comprehensive enough. For example, the SUGAR project did a comprehensive study on the MR-SBW passenger aircraft, but it focused only on the SBW concept and did not consider short-range (SR) and long-range (LR) missions. Virginia Polytechnic and State University [13] conducted the conceptual design and optimization research for a long-range SBW passenger aircraft in the same manner. Besides, there is no comprehensive research on TF passenger aircraft that has been published. Therefore, a comprehensive conceptual design and comparative study of the SBW and TF configurations for typical SR, MR, and LR missions are necessary to comprehensively explore the possibility of adopting SBW and TF configurations in next-generation air transportation.

Robust- and sustainable-by-design ultra-higH aspEct ratio wing and Airframe (RHEA) is a Europe Union-funded project within the Clean Sky 2 Joint Undertaking (https://www.rhea-cleansky2.org/). The RHEA team consists of Technische Universität Braunschweig (DE), University of Strathclyde (UK), Imperial College (UK), DNW Wind Tunnels (NL), and IRT-Saint Exupery (FR), aiming at conceiving innovative next-generation aircraft configurations capable of accelerating the readiness of UHARW by integrating advanced technologies under the paradigm of robustness- and sustainability-by-design [14]. The RHEA project's top-level goals are listed in Table 1. A rendering of the mid-range SBW configuration and TF configuration with UHARW designed by the authors in the RHEA project is shown in Fig. 1.

Table 1 RHEA project goals

Aerodynamics (L/D)	+50 %
R & D Costs	-5 to -10 %
Fuel weight / Emissions (CO2, NOx)	-40 %
Noise	-2 to -4 dB

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Fig. 1. SBW and TF configurations of RHEA mid-range mission.

This paper presents the conceptual design and comparative study of the SBW and TF aircraft configurations with UHARW design for three different classes of aircraft, i.e., short-range, mid-range, and long-range. A conceptual design and analysis framework for the SBW configuration and TF configuration with novel airframe technologies is developed by integrating and improving several methods and tools. Corresponding to the proposed mission profile and top-level requirements, an SBW configuration and a TF configuration are designed for each mission, and a comparative study is conducted between these two configurations. Finally, the best-in-class aircraft configuration for each of the three proposed missions is determined.

III. Methodology for Conceptual Design and Analysis

A. Novel Airframe Technologies

Numerous studies on novel airframe technologies are being conducted for the next-generation transport aircraft in aerodynamics, structure, materials, etc. One of the RHEA project goals is to explore the impact and potential of unconventional aircraft configurations combined with novel airframe technologies to improve fuel efficiency and reduce emissions. The novel airframe technologies considered in this project are briefly described in the following.

Natural Laminar Flow (NLF) is a promising means for significantly reducing viscous wing drag for short-range and mid-range aircraft [15]. However, maintaining a large NLF range on the large aircraft wings is difficult due to their high wing sweep angles. For this reason, Hybrid Laminar Flow Control (HLFC) should be introduced and integrated into wings and tails to delay the flow transition [16]. So the laminar boundary of wings and tails is not only extended by NLF design but also extended by the boundary layer flow control technology, in which the air is sucked from the surfaces to delay the boundary layer transition and to allow a much higher percentage of the laminar flow range than on conventional aircraft surfaces, which has the potential to reduce the overall aircraft drag by up to 50% [15].

Aircraft structures need to be sized for the worst-case operating condition, reflected in the load factors. Aircraft design calculations indicate that wing weight savings are in the order of 45% if the current maximum load factors of +2.5g and -1.0g are reduced to +1.5g and -0.5g by using advanced load alleviation systems [17]. Load alleviation introduces various techniques to reduce the loads experienced by the aircraft and allows for a lighter wing design for the reduced load factors, thereby improving the aircraft's fuel efficiency. Load alleviation techniques can be divided into two kinds: passive and active [18]. Passive load alleviation includes nonlinear stiffness material design, viscoelastic damping design, local morphing concepts, etc. In contrast, active load alleviation contains different flow control techniques to achieve the desired load distribution on the wing [17].

Over the past decades, composites have gradually replaced traditional metallic material in aircraft structures. To consider the next-generation transport aircraft structural materials, tow steering is a novel approach of variable stiffness composite design, which results in a 15% reduction in structural weight compared to conventional composite structures [19]. Besides, thin ply materials could be used in Composite Fiber Reinforced Polymers (CFRP) structures to reduce inter-laminate stresses due to finite ply thickness, potentially reducing the wing weight by approximately 10% [20].

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These presented novel airframe technologies will be included and assumed at the conceptual design stage of the RHEA project to study the potential impact of introducing these novel technologies on the flight performance of the SBW and TF configurations researched in this work.

B. Conceptual Design and Analysis Methodology

PyInit [18], an in-house initial aircraft sizing tool developed by the authors, was used for the initial sizing and performance evaluation of the RHEA aircraft. PyInit contains numerous semi-empirical formulas and physics-based analysis methods for the constraint diagram sizing, components sizing, aerodynamic analysis, static stability, control analysis, propulsion sizing, flight performance evaluation, etc. Several modules and functions in PyInit, including frictional drag estimation and component sizing, were modified, accounting for the SBW and TF aircraft configurations studied in this research. Initial sizing in PyInit starts from analyzing constraints according to the top-level requirements. Then the wing loading and thrust-to-weight ratio can be determined, and the components, including the wing, fuselage, and tailplanes of the aircraft, can be sized. Finally, various analyses, such as aerodynamics, stability, control, and performance characteristics, can be performed.

Then, the initial sized aircraft was imported into the open-source aircraft assessment tool Stanford University Aerospace Vehicle Environment (SUAVE) [21] for the multi-fidelity analysis on the weight breakdown, aerodynamics, flight performance, and missions through convergent iterations. SUAVE contains the analysis modules for several unconventional aircraft configurations, such as solar-powered UAV, electric vertical takeoff and landing (eVTOL) aircraft, etc. However, so far, SUAVE has not included analysis modules for the SBW and TF concepts. Therefore, SUAVE was modified and improved in this research by adding modules on the impact of introducing the above-mentioned advanced technologies and analyzing SBW and TF aircraft configurations, including weight breakdown and parasitic drag estimation methods. In particular, the wing weight estimation methods for SBW and TF aircraft configurations are the most concerned. A class II wing weight estimation method for SBW aircraft developed by Chiozzotto [22], which considers the CFPR materials and aeroelastic effects, was used in this paper for the SBW aircraft sizing. A physics-based wing weight estimation method for TF aircraft developed by Udin [23] was used for the TF aircraft sizing, which calculates the wing weight corresponding to the spanwise load distribution on the wing, including aerodynamic load, fuel mass, wing structural mass, and concentrated mass. The wing material properties in this method were modified to those of the CFPR wings. These two unconventional wing weight estimation methods were integrated into the weight analysis module of SUAVE for RHEA aircraft sizing and analysis.

Besides, the UHARW has a problem regarding compliance with the airport dimensional restrictions. For example, corresponding to the ICAO Class C restriction, the wingspan of the mid-range passenger aircraft cannot exceed 36 meters, and the main landing gear span cannot exceed 9 meters. Therefore, making the wing foldable is essential, and the wing weight increment due to the wing folding should be taken into account. The estimation method of wing mass penalty due to the folding-wing mechanisms represented in Ref. [24] was used in this paper.

OpenVSP [25] and CATIA were used for aircraft geometric modeling and visualization. The sizing and analysis process for RHEA aircraft used in this research is shown in Fig. 2.

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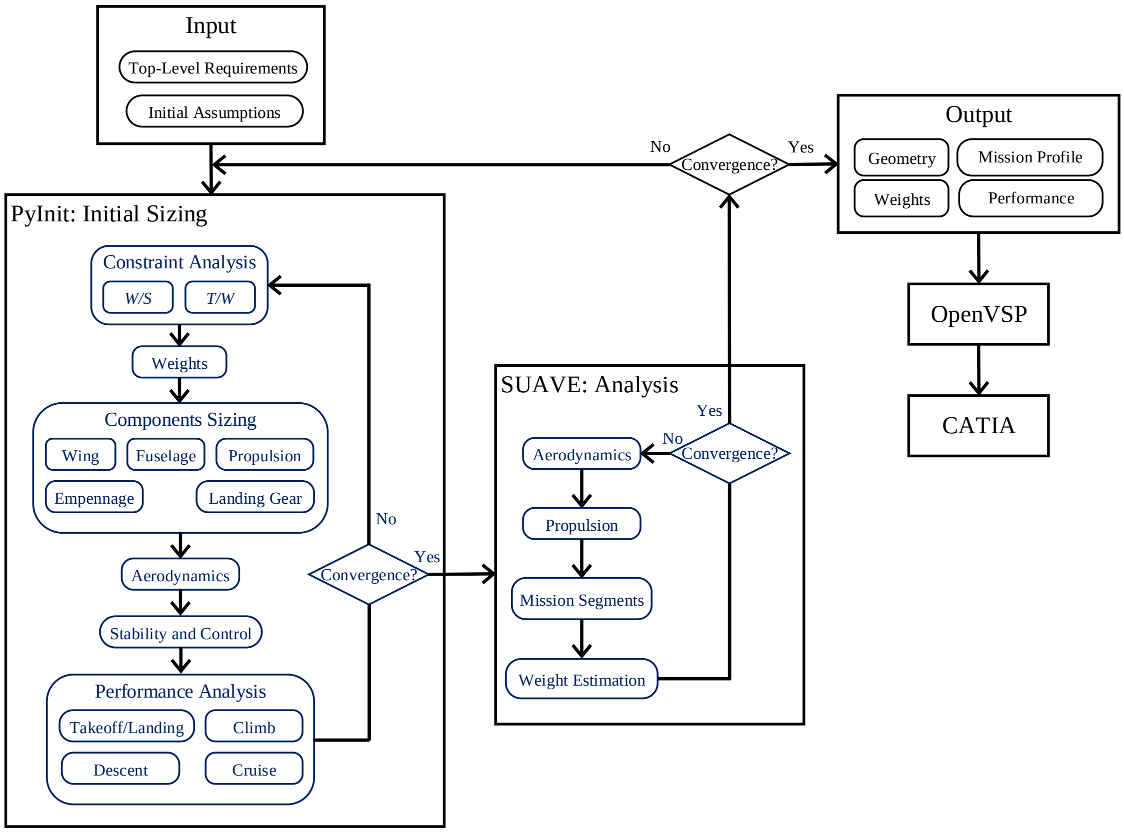

Fig. 2. RHEA aircraft sizing and analysis procedure.

An SBW aircraft and a TF aircraft were used to validate the modified SUAVE method for RHEA aircraft. The SUGAR aircraft with a high aspect ratio wing was selected for the SBW aircraft analysis module validation. The SUGAR aircraft, featuring an SBW configuration, was designed for the mid-range mission with 154 passengers (2 class) and a range of 3500 nm, which has been studied in detail by high-fidelity aerodynamic and structural analysis and wind tunnel experiments [26]. The SUGAR aircraft data required for the analysis were extracted from Ref. [8]. The payload, range, and geometric parameters of SUGAR aircraft were input into the modified SUAVE, and the calculations were iterated until the weight and mission segments are converged. The comparison of the SUGAR aircraft and the resulted aircraft by SUAVE are tabulated in Table 2, which shows the presented modified SUAVE gives acceptable results for this SBW aircraft.

Table 2 Validation of the SBW analysis module in the modified SUAVE

Group	SUAVE result	SUGAR [8]	Relative error/%
MTOW, kg	66998	68039	-1.53
Fuel weight, kg	15599	15365	1.52
Empty weight, kg	36799	36328	1.30
C_L	0.0685	0.750	-8.67
C_D	0.0290	0.0298	-2.58
C_{D_0}	0.0218	0.0200	8.99
C_{D_i}	0.0107	0.0098	8.77

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L/D	23.5882	25.159	-6.24

A large cargo TF aircraft designed by Lockheed and NASA to replace the Lockheed C-5A and the Boeing 747 transport aircraft was chosen to validate the TF aircraft analysis module in the modified SUAVE. The technology assumptions and required data were extracted from Ref. [27], and a comparison of the reference aircraft and the resulted aircraft are listed in Table 3, which shows an acceptable accuracy.

Table 3 Validation of the TF analysis module in the modified SUAVE

Parameter	SUAVE	Reference value [27]	Error, %
MTOW, kg	863885	891128	-3.06
OEW, kg	314174	335250	-6.29
Fuel Weight, kg	199732	205900	-2.99
C_L	0.485	0.509	-4.72
C_D	0.0226	0.0220	2.64
L/D	21.48	23.14	-7.17

IV. Conceptual Design and Comparative Study

In this section, an SBW configuration and a TF configuration are designed for each mission, i.e., a total of 6 aircraft are designed in the following subsections. And comparative studies are carried out to determine the best-case and worst-case configurations for each mission.

A. Overview of Design Requirements and Assumptions

RHEA aircraft is designed to comply with CS-25 certificate regulations [28]. ATR 72-600, A320neo, and B777-300ER are selected as the baseline reference aircraft for short-, mid-, and long-range missions, respectively. The EIS of RHEA aircraft is taken as the year 2040.

As introduced in Section I, RHEA aircraft will be designed with a UHARW configuration. Referring to some future aircraft designs [8, 18, 29], the RHEA aircraft's wing aspect ratio is initially taken as 25 in the initial conceptual design stage, which will be optimized in the later optimization study phase.

As described in the Sec. III.A, several novel airframe technologies of the next-generation passenger aircraft need to be considered in this research. The assumptions of the above-mentioned novel airframe technologies for each mission and each configuration are tabulated in Table 4.

Table 4 Assumptions of novel airframe technologies used in the conceptual design

Configuration		HLFC (Percentage of laminar flow area on the wing and tailplane)	Load alleviation (max. load factors)	Advanced materials & structures
Short-range	SBW	65%	+1.5g and -0.5g	20% structural weight reduction
	TF	70%		
Mid-range	SBW	50%	+1.5g and -0.5g	20% structural weight reduction
	TF	55%		
Long-range	SBW	50%	+1.5g and -0.5g	20% structural weight reduction
	TF	55%		

The mission profile of RHEA aircraft is shown in Fig. 3. The entire mission is divided into several segments, including the main mission and a reserve phase. For the reserve flight, the current requirements for mid-range passenger aircraft are 5% of trip fuel, a 200 nm divert segment, and a 30 min hold [30]. However, considering the aircraft studied in this research will operate in the future environment, these requirements will be reduced based on

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the assumption that the air traffic control technology will be improved by then, and the assumed values for each mission will be shown in the following subsections.

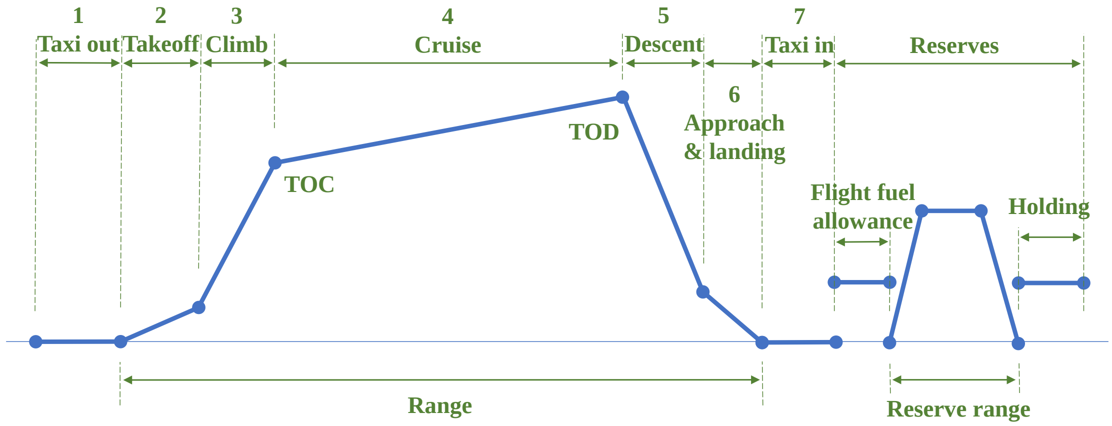

Fig. 3. RHEA aircraft mission profile.

B. Medium-Range Mission

As a medium-range mission is currently the most concentrated research field for the next-generation passenger aircraft, this research starts with this mission because there are abundant reference aircraft.

1. *Initial Aircraft Sizing*

Several high aspect ratio wing aircraft, including SUGAR aircraft [8], SE2A mid-range aircraft [18], D8.5 aircraft [29], and SD8.5 aircraft [1], were chosen as the reference for the RHEA mid-range aircraft design and comparison. A320neo aircraft was selected as the baseline aircraft for the RHEA mid-range mission, and the top-level requirements of RHEA mid-range aircraft were mainly referred to as that of A320neo. The top-level requirements of the RHEA mid-range mission and that of the selected reference aircraft are listed in Table 5.

Reducing the cruise Mach number can bring benefits for aircraft fuel efficiency [8]. Therefore, several next-generation passenger aircraft research slightly decreased the design cruise Mach number, such as SUGAR and D8 aircraft, as given in Table 5. However, since the RHEA project focuses on the advantages/differences of introducing ultra-high aspect ratio wing and novel airframe technologies for the next-generation passenger aircraft, the cruise and maximum Mach number are the same as those of the baseline aircraft A320neo, for comparison purposes. The fuel efficiency improvement effect of reducing cruise Mach number will be investigated at a later stage. As RHEA aircraft is designed with UHARW, it should be noted that there are regulations for the aircraft wingspan due to the airport facilities constraints [8]. For the mid-range aircraft operating at ICAO Class C airports, the wingspan constraint is 36 m, and the outer main gear wheel span should not exceed 9 m which is very important for the TF configuration sizing.

The novel airframe technology assumptions are given in Table 4, which were applied to PyInit and SUAVE during the MR aircraft conceptual design and performance assessment.

Table 5 Top-level requirements of the mid-range mission

Parameter		Unit	RHEA	References			
				SUGAR [8]	SE2A [18]	D8.5 [29]	SD8.5 [1]
Reference aircraft		—	A320neo	B737NG	A320	B737-800	B737-800
Cruise Mach number		—	0.78	0.71	0.78	0.74	0.74
Max. Mach number		—	0.82		0.82		
Passengers (1 class)		—	186		186	180	180
Passengers (2 class)		—	150	154	150		
Range		nm	3400	3500	2490	3000	3000
Reserves	Contingency fuel	—	3%	3%	5%	5%	5%

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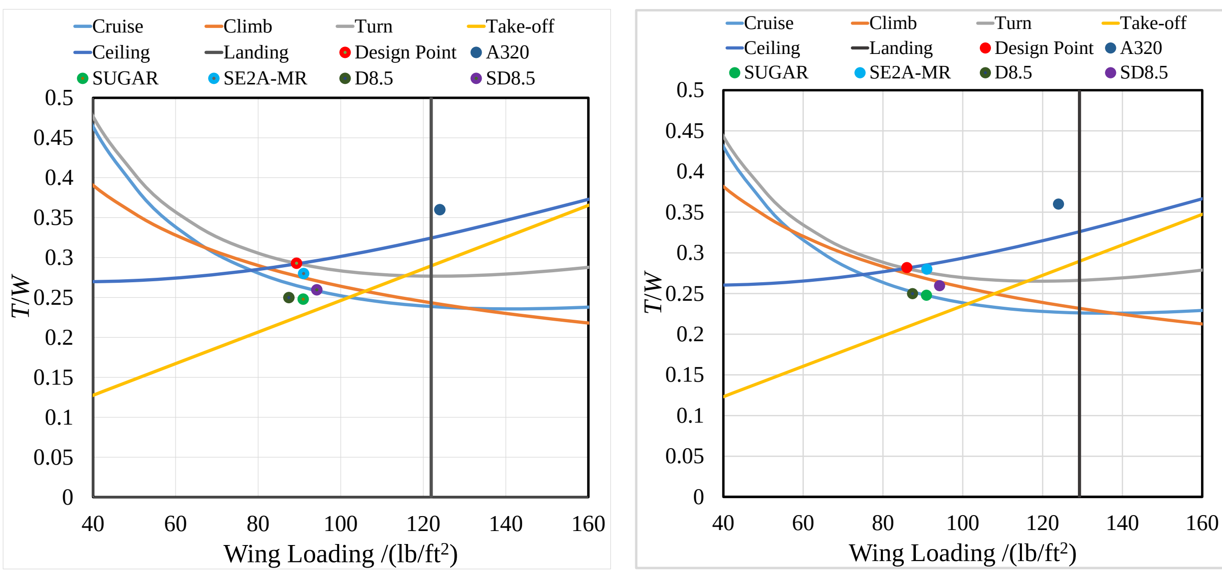
	Divert segment	nm	200	200	200		
	Hold (at 1500 ft)	min	10	10	30		
Cruise altitude		ft	33000	Vary	35000	44653 to 46415	44653 to 46415
Service ceiling		ft	38500	43000	37000		
Takeoff field length		ft	<6400	<8190	<6000	5000	4850
Landing distance		ft	<4500		<4500	3555	
Approach speed		kt	136	135	140		
Airport (ICAO C)	Wingspan	m	36	36	36		
	Main landing gear span	m	9				
Certification regulation		—	CS 25	FAR 25	CS 25	FAR 25	FAR 25

As described in Section III, the aircraft initial sizing tool PyInit, modified for SBW and TF concepts in this research, was used for the initial sizing of the MR-SBW and MR-TF aircraft. Corresponding to the top-level design requirements and novel technology assumptions given in Table 4 and Table 5, the wing loading and thrust-to-weight ratio of the MR-SBW and MR-TF aircraft were sized, and the design points are shown in Fig. 4. Besides, the design points of the selected reference aircraft are also shown in Fig. 4 for comparison.



a) MR-SBW   b) MR-TF

Fig. 4. RHEA-MR aircraft constraint diagrams.

OpenVSP was used for the visualization of the initially sized aircraft configurations. The three-view dimensions of the aircraft are shown in Fig. 5. Considering the UHARW concept, both the MR-SBW and MR-TF aircraft feature a high-wing configuration with two wing-mounted high bypass ratio turbofan engines. The wings are designed foldable with the folding position 36/2 m of the half-wingspan. The supercritical airfoils NASA SC(2)-0412 and NASA SC(2)-0410 were adopted for the wing root airfoil and wingtip airfoil, respectively, and NASA SC(2)-0010 was used for the tailplane airfoil. Besides, the wing sweep angle (0.25*c*) was taken as 12.5 deg to facilitate the laminar flow on the wing surface.

A T-tail was chosen for the MR-SBW aircraft due to the high-wing configuration. The strut was designed to be attached at 49.79% of the half-wingspan position. The chord of the strut is sized by buckling, resulting in the strut shaped like a bow tie [8].

The high-slab configuration was used for the MR-TF aircraft tailplanes. The horizontal tail was designed with a forward-swept configuration, which can increase the horizontal tail moment arm to reduce the horizontal tail area and reduce the wave drag of the horizontal tail (compared to a zero-swept horizontal tail).

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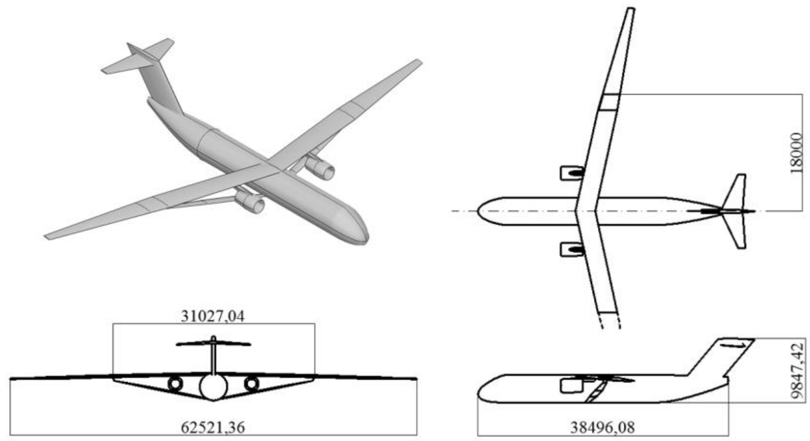
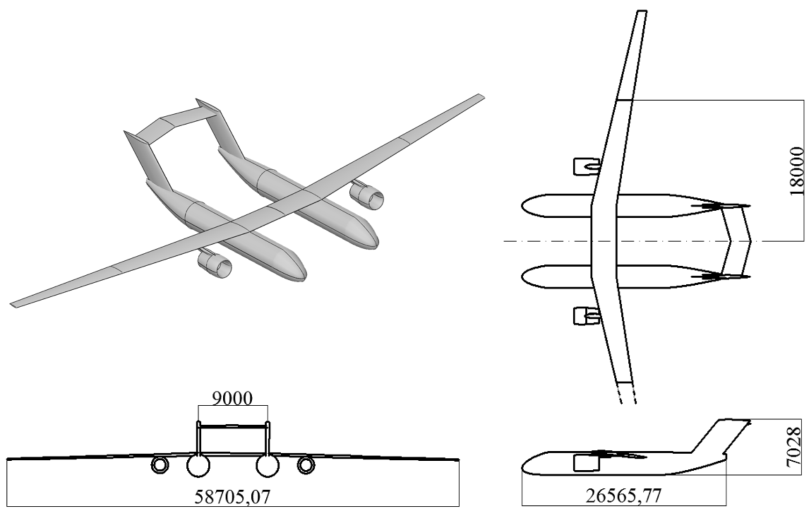


a) MR-SBW



b) MR-TF

Fig. 5. Three-view dimensions of RHEA mid-range aircraft.

To facilitate comparison and simplification, the fuselage of A320neo was used for the MR-SBW aircraft and taken as the reference for the MR-TF aircraft fuselage sizing. The TF aircraft fuselage sizing methodology presented in Ref. [9] is used in this paper, i.e., the length and equivalent diameter of each fuselage equal to that of the reference fuselage divided by $\sqrt{2}$, ensuring the same cabin floor area as the reference fuselage. A320neo features a 6-abreast seating arrangement for the economy class. Due to the fuselage size is scaled down, the seating arrangement for the economy class of the MR-TF aircraft is taken as 4-abreast to ensure the sized cabin meets the cabin design requirements [31]. The two-class cabin layout of the MR-TF aircraft is shown in Fig. 6, with a total of 150 seats, similar to that of A320neo and MR-SBW aircraft. It is worth noting that the nose of the non-cockpit fuselage was arranged with two super-first-class seats with the best view, making full use of the space in the fuselage, providing more choices for passengers, and bring more profits for airlines.

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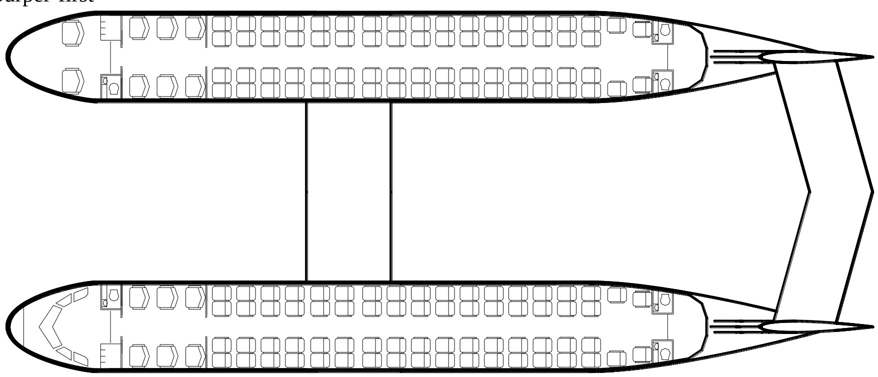

Fig. 6. MR-TF aircraft interior arrangement.

2. Aircraft Assessment and Comparison

As described in Fig. 2, the modified SUAVE, improved for the novel airframe technologies and SBW and TF aircraft configurations, was used to converge the aircraft weights while satisfying the required flight missions, as shown in Fig. 3 and listed in Table 5. The flight conditions and aircraft configurations of the MR-SBW and MR-TF aircraft obtained during the initial sizing process by PyInit were input into SUAVE for iterative calculations, respectively. The SUAVE analysis results of the RHEA-MR aircraft are given in Table 6. Besides, the key weight data of the baseline aircraft A320neo [32] is also tabulated in Table 6 for reference and comparison.

As listed in Table 6, both SBW and TF configurations with the novel airframe technologies have significant advantages over the A320neo for the proposed mid-range mission, as shown in Fig. 7. It is interesting to note that the MR-TF aircraft has significantly better fuel efficiency than that of MR-SBW aircraft, mainly due to the lighter operating empty weight. The load distribution on the MR-TF aircraft wings is more optimal than that of the MR-SBW aircraft because the large centrally positioned fuselage weight is replaced by two outboard positioned weights. Since the pressure cabin skin thickness of a passenger aircraft is proportional to its volume, the total fuselage skin weight of the MR-TF aircraft is lighter than that of the MR-SBW aircraft with the same total fuselage skin area [9], resulting in a lighter total fuselage weight for the MR-TF aircraft. As given in Table 6, on the one hand, the large difference between the wing and fuselage weights of the SBW and TF aircraft is due to the explained reasons. On the other hand, it is also due to the smaller TF aircraft MTOW, resulting in a smaller weight per component. Besides, it should be noted that the MR-TF aircraft features a heavier horizontal tail because of its shorter fuselage length and shorter tail moment arm, indicating that the forward-swept horizontal tail design is necessary. Otherwise, the horizontal tail would be much heavier.

Table 6 Weight breakdown comparison of RHEA-MR aircraft

Group	MR-SBW	MR-TF	A320neo [32]
Max. takeoff weight, kg	67929	57777	79000
Fuel weight, kg	16127	13328	20980
Empty weight, kg	37582	30229	44300
Empty weight breakdown			
Wing, kg	9393	4631	
Fuselages, kg	7066	5241	
Propulsion, kg	4493	3710	
Nacelles, kg	527	490	
Landing gear, kg	2292	1976	

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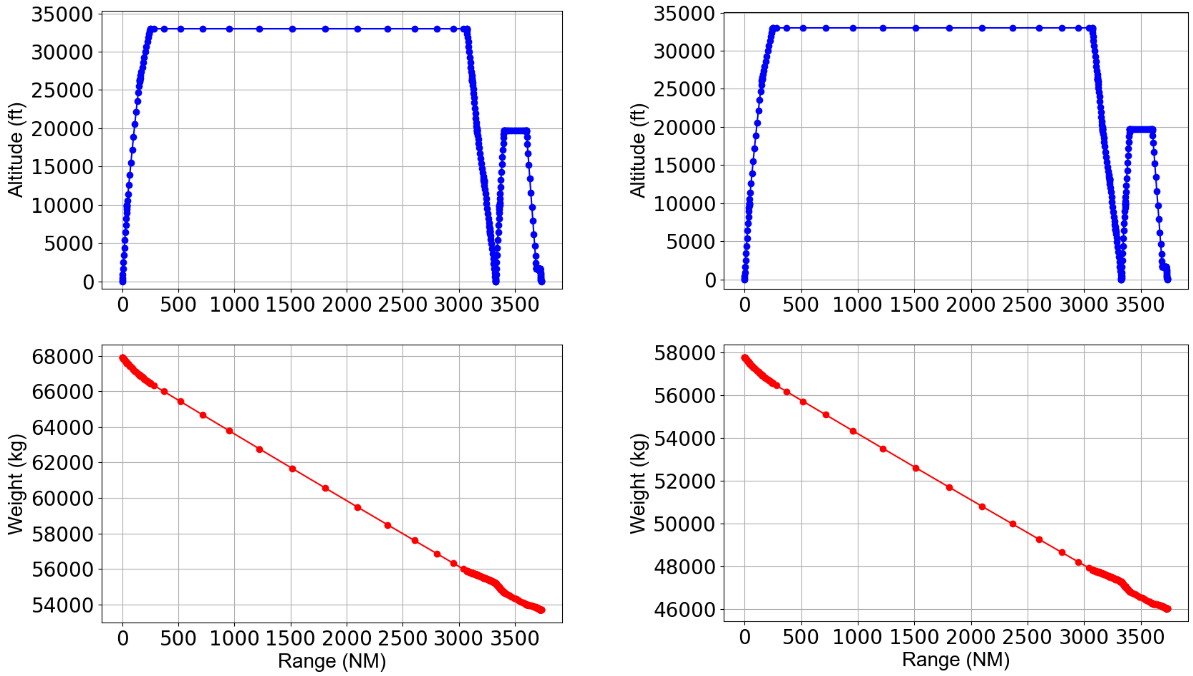
Horizontal tail, kg	414	772
Vertical tail, kg	902	844
Paint, kg	447	415
Systems, kg	12049	12151



a) MR-SBW b) MR-TF

Fig. 7. Mission performance of RHEA-MR aircraft.

Then the geometric dimensions of MR-SBW, MR-TF, and several reference aircraft are compared. As shown in Fig. 8, the RHEA-MR aircraft have a higher wingspan than the presented reference aircraft due to the UHARW design. The wingspan of MR-TF aircraft is shorter than that of MR-SBW aircraft because of its lighter MTOW. Due to the TF design, the MR-TF aircraft's fuselage length is significantly less than other aircraft, and the smaller size facilitates airport operations.

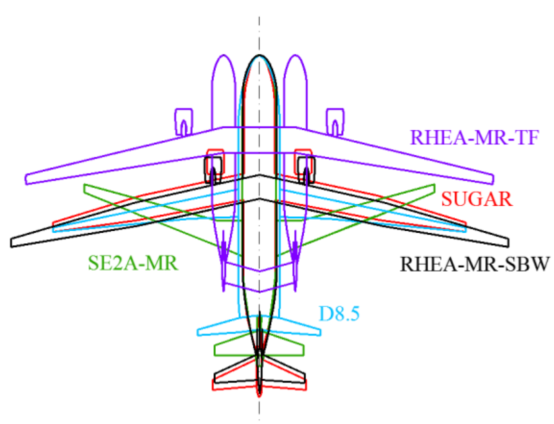


Fig. 8. Geometry comparison of RHEA-MR aircraft.

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Since the MR-TF aircraft's fuselages were sized to have the same total cabin floor area as the reference fuselage, the total volume of the MR-TF aircraft is equal to that of the reference fuselage divided by $\sqrt{2}$, meaning that the MR-TF aircraft's total cargo compartment volume is smaller than that of the reference aircraft, i.e., its cargo capacity is lower. During the TF aircraft sizing process, a constraint was applied to ensure that the luggage weight for each passenger is larger than 23 kg, and the value for the MR-TF aircraft is 23.30 kg.

Therefore, the MR-TF aircraft outperforms the MR-SBW aircraft due to its significant performance advantages and its smaller size. However, it should be noted that this is only the performance results of the initial design configurations based on the reference data and the designer's experience, from which preliminary comparative results can be obtained. Still, it is not enough to comprehensively and accurately reflect the gap between SBW and TF configurations. More precise comparisons and research based on MDO study results are needed in future research.

C. Long-Range Mission

1. Initial Aircraft Sizing

Similar to the MR mission, several reference passenger aircraft designed for the next-generation long-range (LR) mission were selected for reference and comparison, including VT-SBW aircraft [13], H3.2 aircraft [1], Centerline aircraft [33], and DisPURSAL aircraft [34]. B777-300ER was selected as the baseline aircraft for the LR mission. The top-level requirements of the RHEA long-range mission and that of the selected reference aircraft are listed in Table 7. A design requirements comparison between the RHEA-LR aircraft (orange dot), the selected reference aircraft (green dots), and numerous existing aircraft (blue dots) are shown in Fig. 9. Besides, the novel airframe technology assumptions tabulated in Table 4 were applied to PyInit and SUAVE during the LR aircraft conceptual design and performance assessment.

Table 7 Top-level requirements of the long-range mission

Parameter		Unit	RHEA	References			
				VT-SBW [13]	H3.2 [1]	Centerline [33]	DisPURSAL [34]
Reference aircraft		—	B777-300ER	B777-200ER	B777-200LR	A330-300	A330-300
Cruise Mach number		—	0.84	0.85	0.83	0.82	0.8
Max. Mach number		—	0.89				
Passengers (2 class)		—	350			340	340
Passengers (3 class)		—		305	354		
Range		nm	7500	7730	7600	6500	4800
Reserves	Contingency fuel	—	3%		5%		
	Divert segment	nm	200	350			
	Hold (at 1500 ft)	min	10		60		240
Cruise altitude		ft	35000	48000	34921	35000	35000
Service ceiling		ft	40000		40850	41000	
Take-off field length		ft	9000	11000	9000	9514	7546
Landing distance		ft	9000	11000	4966	7874	6562
Approach speed		kt	140	135	156	145	140
Airport (ICAO E)	Wing span	m	65	80 (F)		65	65
	Main landing gear span	m	14				
Certification requirements		—	CS 25	FAR 25	FAR 25	CS 25	

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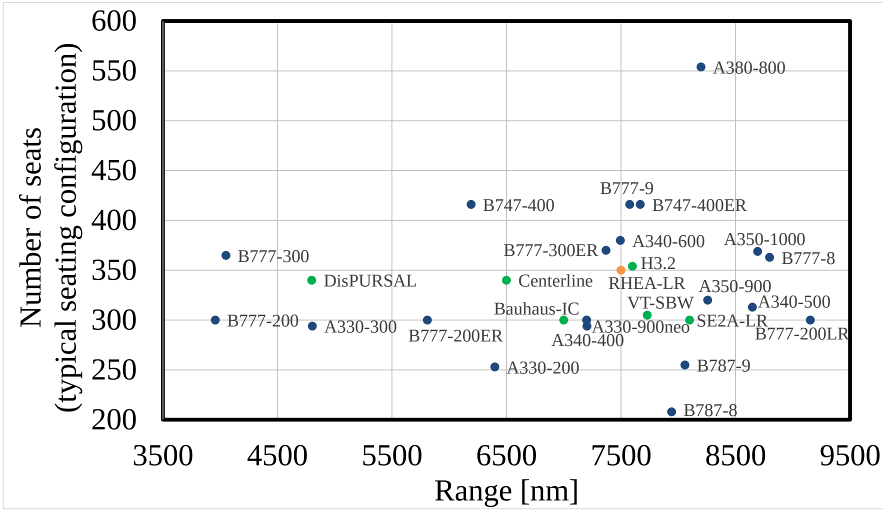
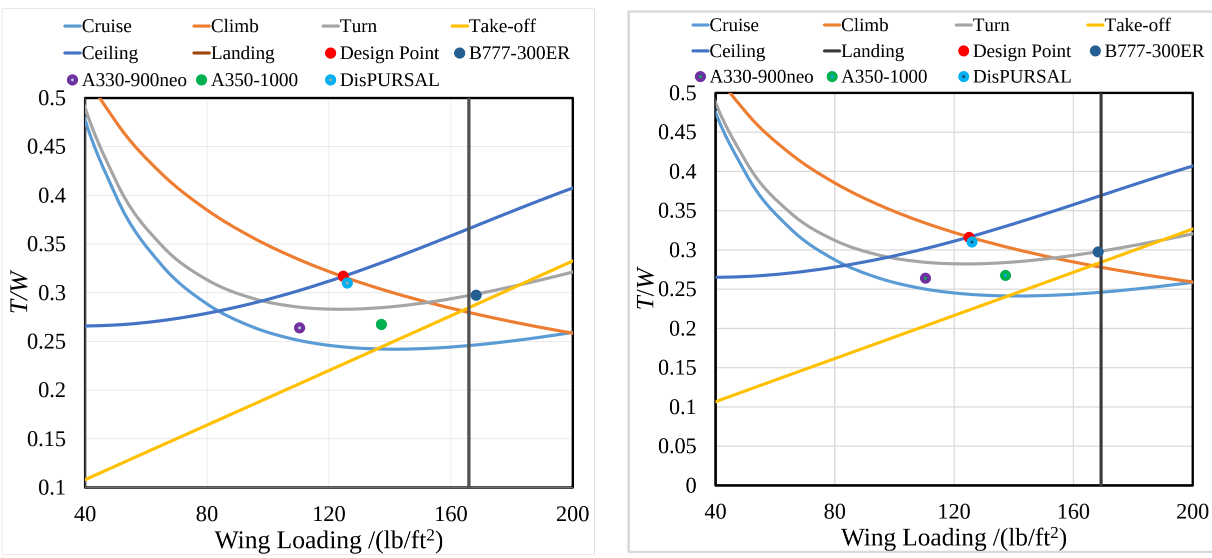


Fig. 9. The number of seats and range of the RHEA-LR aircraft compared to existing aircraft.

Corresponding to the novel airframe technology assumptions and the top-level aircraft requirements, the wing loading and thrust-to-weight ratio of the LR-SBW and LR-TF aircraft were sized by PyInit. The design points are shown in Fig. 10. Besides, the design points of the selected reference aircraft are also shown in Fig. 10 for comparison.



a) LR-SBW

b) LR-TF

Fig. 10. RHEA-LR aircraft constraint diagrams.

Like the MR mission considerations, the high-wing configuration with two wing-mounted high bypass ratio turbofan engines was chosen for the LR aircraft, and the wing was designed foldable with the folding position at 65/2 m of the half-wingspan. The same wing and tail airfoils as MR aircraft were initially used for the LR aircraft. A wing sweep angle (0.25*c*) of 23 deg was chosen as a trade-off between the wave drag and the laminar flow on the wing surface.

The LR-SBW aircraft features a similar configuration to the MR-SBW aircraft, as shown in Fig. 11. The strut is attached at 58.44% of the half-wingspan position.

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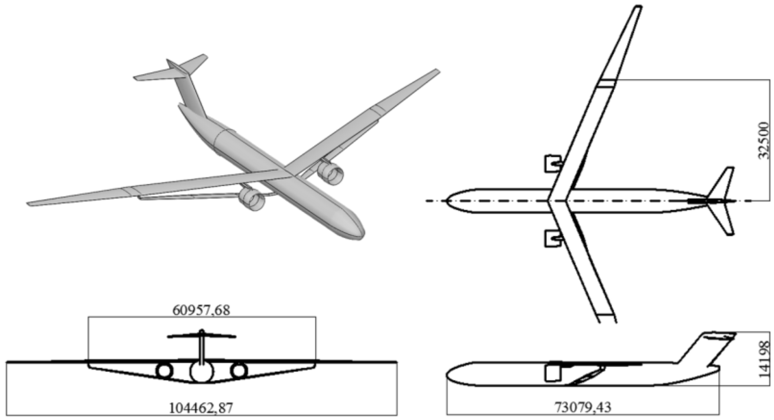

Fig. 11. Three-view dimensions of LR-SBW aircraft.

The forward-swept high-slab tailplane configuration was initially chosen for the LR-TF aircraft (see “E” in Fig. 12). However, due to the main landing gear span limitation (i.e., fuselage spacing) and the short fuselage length, the aspect ratio of the horizontal tail is too small, which will cause poor aerodynamic performance for the horizontal tail. Then, several different horizontal tail configurations were proposed that have more desirable aspect ratios, as shown in Fig. 12. When making trade-offs between these configurations, the main considerations are the aeroelastic and drag (especially wave drag) of the horizontal tail, and finally, the configuration “F” won out. The three-view dimensions of the final LR-TF aircraft configuration are shown in Fig. 13.

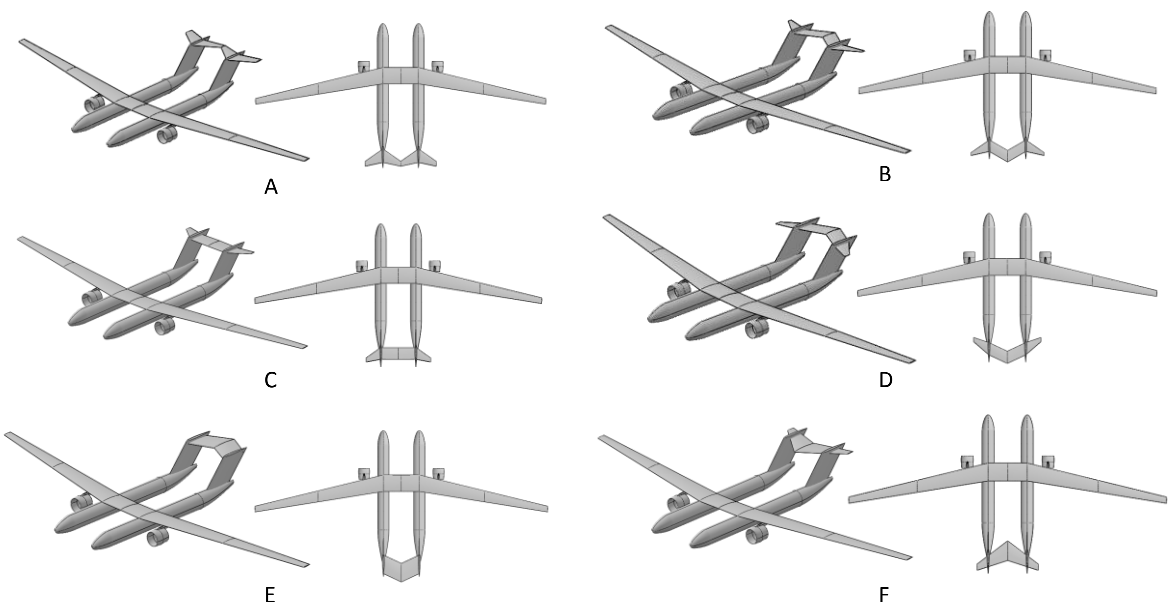

Fig. 12. LR-TF aircraft with different horizontal tail configurations.

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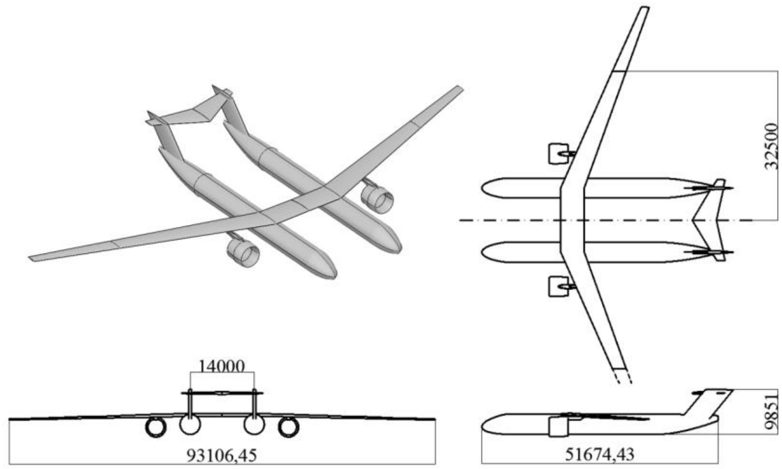

Fig. 13. Three-view dimensions of LR-TF aircraft.

The fuselage of the baseline aircraft B777-300ER was used for the LR-SBW aircraft and taken as the reference for the LR-TF aircraft fuselage sizing. The same fuselage sizing method as MR-TF aircraft was used for the LR-TF aircraft fuselage sizing. According to the design requirements in Fig. 9, the LR-SBW and LR-TF aircraft were designed to have the same number of first- and economy-class seats, as shown in Table 8. The reference aircraft B777-300ER and the LR-SBW aircraft feature a 6-abreast and 9-abreast seating arrangement for the first- and economy-class, respectively, while the LR-TF aircraft has a 4-abreast and 6-abreast seating arrangement for the first- and economy-class, respectively, as shown in Fig. 14. Similar to the MR-TF aircraft's design, the nose of the non-cockpit fuselage was arranged with two super-first-class seats.

The fuselage of the LR-TF aircraft is a circular cross-section, obtained by scaling the fuselage of the B777-300ER, which is a bit wide for the LR-TF aircraft's 6-abreast economy-class fuselage. Therefore, the width of the LR-TF aircraft fuselage was reduced appropriately to obtain an elliptical cross-section fuselage. The LR-TF aircraft's fuselage cross-section and its cabin parameters are shown in Fig. 15. It is worth noting that the LR-TF aircraft has the same cabin interior arrangement and similar fuselage cross-sectional size as the A320neo, but the fuselage length is slightly longer than that of the A320neo. Therefore, the LD3-45W cargo container was selected for the LR-TF aircraft. The cargo capacity per passenger of the LR-TF aircraft is slightly better than that of A320neo and significantly better than that of the MR-TF aircraft.

Table 8 Cabin seats number comparison.

Cabin class	LR-SBW	LR-TF
First	2+40	42
Economy	308	308
Total	350	350

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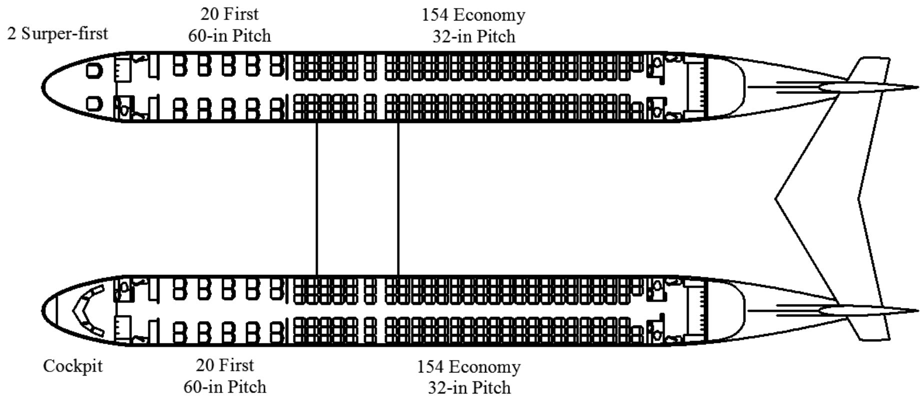

Fig. 14. LR-TF aircraft interior arrangement.

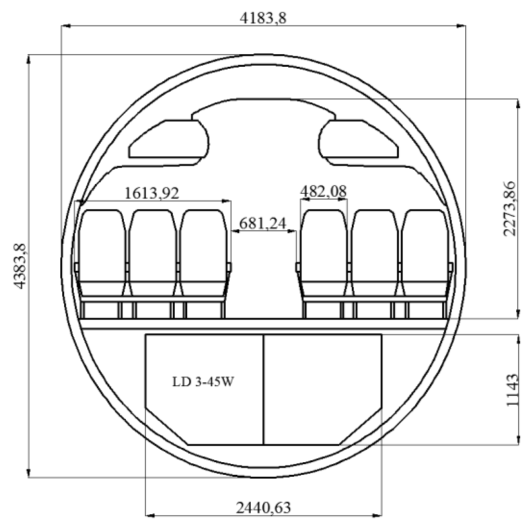

Fig. 15. Fuselage cross-section of LR-TF aircraft.

2. Aircraft Assessment and Comparison

The flight conditions and aircraft configurations of the LR-SBW and LR-TF aircraft obtained during the initial sizing by PyInit were input into the modified SUAVE for iterative calculations. The SUAVE analysis results of the LR aircraft and the key weight data of the baseline aircraft B777-300ER [35] are tabulated in Table 9.

As given in Table 9, both SBW and TF configurations with the novel airframe technologies have significant advantages over the B777-300ER for the proposed long-range mission shown in Fig. 16. The results are similar to the MR mission in that the TF aircraft has a better fuel efficiency due to its significantly lighter operating empty weight than the SBW configuration. It is worth noting that the difference in wing weight between the LR-SBW and LR-TF aircraft is greater than that of the MR aircraft, which is due to the better unloading effect on the wing due to the heavier outboard positioned fuselages. Besides, due to the smaller fuselage equivalent diameter, the LR-TF aircraft fuselage is also lighter than that of the LR-SBW aircraft.

Table 9 Weight breakdown comparison of RHEA-LR aircraft

Group	LR-SBW	LR-TF	B777-300ER [35]
Max. takeoff weight, kg	262962	210955	351535
Fuel weight, kg	89716	80037	145538
Empty weight, kg	140066	97737	167829

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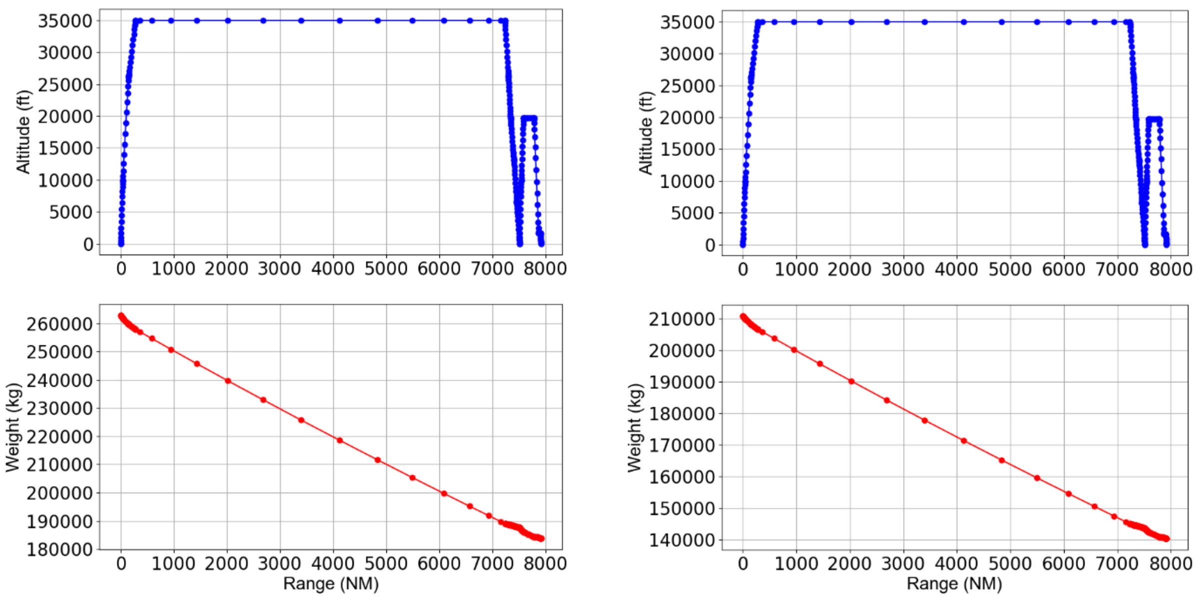
Empty weight breakdown		
Wing, kg	47401	16630
Fuselages, kg	25757	20596
Propulsion, kg	18650	15038
Nacelles, kg	2460	2270
Landing gear, kg	7023	5735
Horizontal tail, kg	1483	1478
Vertical tail, kg	2923	2392
Paint, kg	1237	1153
Systems, kg	33133	32446



a) LR-SBW

b) LR-TF

Fig. 16. Mission performance of RHEA-LR aircraft.

As shown in Fig. 17, the geometric dimensions of LR-SBW, LR-TF, and B777-300ER are compared. Due to the UHARW design, the RHEA-LR aircraft's wings need to be designed as foldable, as marked in the figure. It should be noted that both the wingspan and the fuselage length of the LR-TF aircraft are smaller than those of the LR-SBW aircraft because of its smaller MTOW and the TF concept characteristics.

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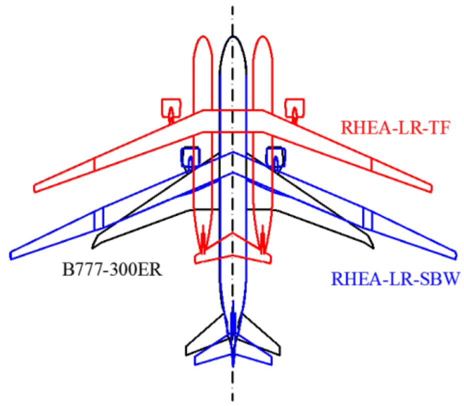

Fig. 17. Geometry comparison of RHEA-LR aircraft.

Therefore, the LR-TF aircraft outperforms the LR-SBW aircraft due to its obvious performance advantages and smaller size. It should be noted that this comparison result was only based on the initial conceptual design results, which may not be enough to reflect the differences between these two unconventional configurations, and the further MDO study needs to be carried out in the following research stage.

D. Short-Range Mission

1. Initial Aircraft Sizing

Several reference passenger aircraft designed for the next-generation Short-Range (SR) mission, including Saeed-007.1 [6], PEGASUS [36], TU Delft [37], and TPR70neo+ [38], were chosen for reference and comparison. ATR72-600 was selected as the baseline aircraft for the SR mission. The top-lever requirements of the RHEA short-range mission and those of the selected reference aircraft are tabulated in Table 10. Besides, the novel airframe technologies assumed in Table 4 were applied to PyInit and SUAVE for the SR aircraft conceptual design and performance analysis.

Table 10 Top-level requirements of the short-range mission

Parameter		Unit	RHEA	References			
				Saeed-007.1 [6]	PEGASUS [36]	TU-Delft [37]	TPR70neo+ [38]
Reference aircraft		—	ATR 72-600	ATR 42/72	ATR72-500	ATR 72-600	ATR 72 & Dash 8
Propulsion concept		—	Turboprop	Turbofan	Hybrid	Hybrid	Turboprop
Cruise Mach number		—	0.42	0.457	0.45	0.415	0.41
Max. Mach number		—	0.457	0.5		0.457	0.55
Passengers		—	72	72	48	70	70
Range		nm	825	1242	400	825	826
Reserves	Contingency fuel	—	3%	0			
	Divert segment	nm	87	270	87		
	Hold (at 1500 ft)	min	10	0	45		
Cruise altitude		ft	20000	20000	20000	25000	23000
Service ceiling		ft	25000		25000	25000	
Take-off field length		ft	4373	4265			4429
Landing distance		ft	3002				2917
Approach speed		kt	113	120			118
Airport category (ICAO C)	Wingspan	m	36				36
	Main landing gear span	m	9				9
Certification requirements		—	CS 25		Part 25	CS 25	CS 25

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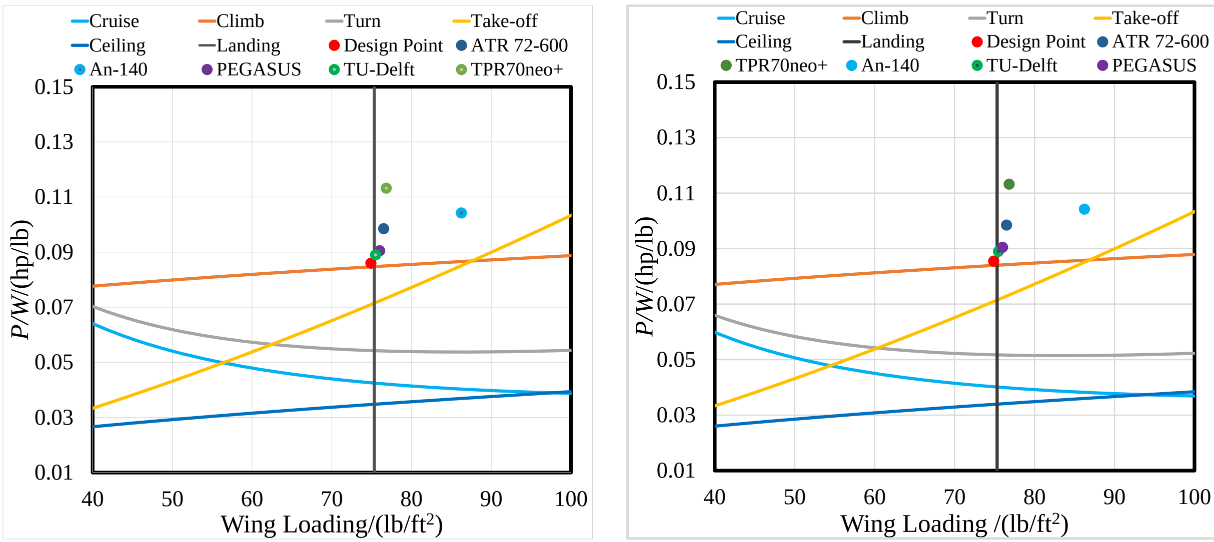
It should be noted that the turboprop engines are used in the RHEA-SR aircraft, so the PyInit was extended to take into account the power-to-weight ratio (*P/W*) for this kind of aircraft. Corresponding to the novel airframe technology assumptions and the top-level aircraft requirements, the wing loading and power-to-weight ratio of the SR-SBW and SR-TF aircraft were sized by the extended PyInit, and the design points are shown in Fig. 18. Besides, the design points of the chosen reference aircraft are also shown in Fig. 18 for comparison purposes.



a) SR-SBW b) SR-TF

Fig. 18. RHEA-SR aircraft constraint diagrams.

Because of the UHARW design, the high-wing configuration with two turboprop engines was chosen for the SR aircraft, and the wing was designed foldable with the folding position at 36/2 m of the half-wingspan. Since the SR aircraft will operate in the subsonic region, NACA 65-618 and NACA 65-613 were selected for the wing roots and tips to maximize laminar flow, and NACA 0010 airfoil was chosen for the tail. Besides, a straight wing was designed to maximize the wing's aerodynamic performance according to the subsonic operating environment.

As shown in Fig. 19, the SR-SBW aircraft is a high-wing configuration with aft-mounted turboprop engines. The completely clean wing enables a substantial laminar flow percentage. In contrast, it is challenging to maintain laminar flow in the wing region affected by the propeller downwash of the configuration with wing-mounted engines. Besides, the strut is attached at 60% of the half-wingspan position.

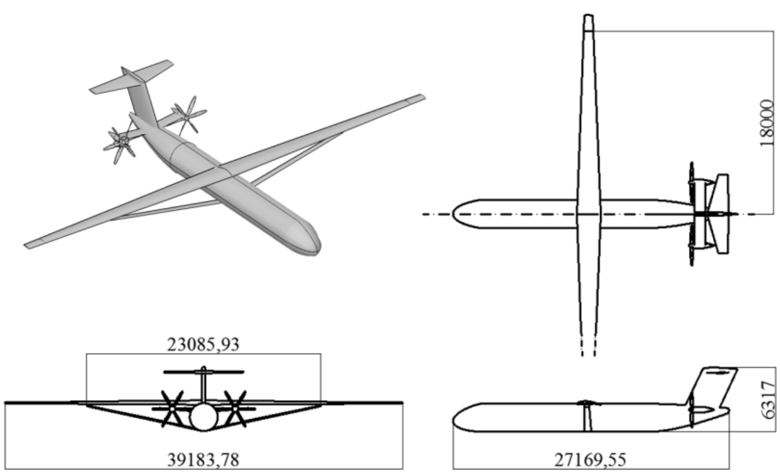


Fig. 19. Three-view dimensions of SR-SBW aircraft.

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The wing-mounted engines and forward-swept high-slab tailplane configuration were initially selected for the SR-TF aircraft (see "A" in Fig. 20). Due to the wide fuselage spacing, the horizontal tail aspect ratio is too large. Thus some structural aspect problems may arise, and the wing laminar flow proportion is not maximized. When separating the horizontal tail to each fuselage and moving the engines to the fuselage tail, the configuration "E" is obtained. However, the asymmetric engine concept will produce unexpected torque to the fuselage structure. When the engine pylons are attached by a low-slab tailplane (see "B" in Fig. 20), the unexpected torque can be significantly reduced. Still, the horizontal tail area will increase, resulting in increased takeoff weight. A good solution is to mount the engines at the joint of the vertical and horizontal tails of the twin tee-tail configuration "D" or canted slab-tail configuration "F". However, such engine positions will produce additional pitch down moment to the aircraft. Therefore, the wing-mounted engines and twin tee-tail configuration were selected for the initial conceptual design and configuration comparative study. Other configurations will be further investigated and compared in future studies, if necessary. The three-view dimensions of the final selected SR-TF aircraft configuration are shown in Fig. 21.

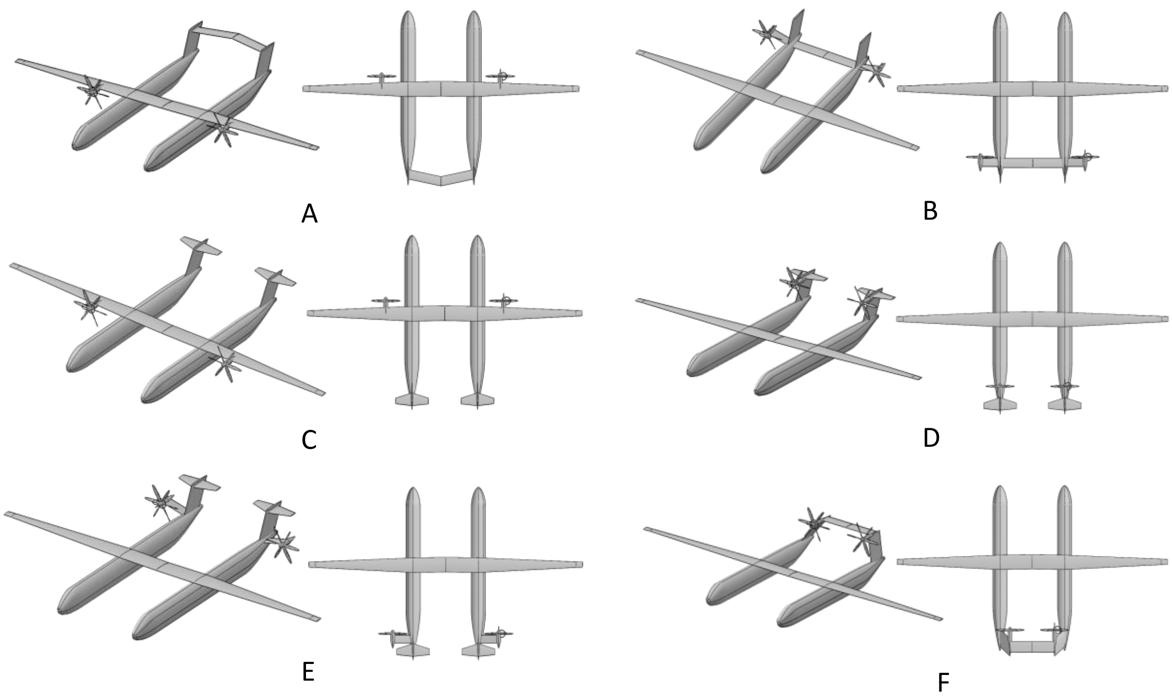

Fig. 20. Different SR-TF aircraft configurations.

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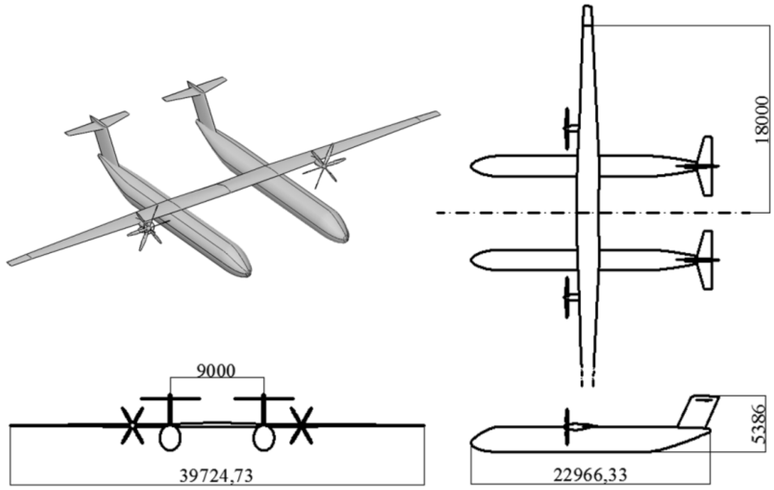

Fig. 21. Three-view dimensions of SR-TF aircraft.

The fuselage of the baseline aircraft ATR 72-600 was used for the SR-SBW aircraft and taken as the reference for the SR-TF aircraft fuselage sizing and the same fuselage sizing methodology as MR-TF aircraft was used. According to the top-level requirements, the SR-SBW and SR-TF aircraft were designed to have the same number of total seats as the ATR 72-600, i.e., 72 seats [39]. The reference aircraft ATR 72-600 and the SR-SBW aircraft feature a 4-abreast and 29-in pitch seating arrangement. After scaling down from the reference fuselage, the width of the TF aircraft fuselage could accommodate 3-abreast seats, but the cabin aisle height cannot meet the requirements. Therefore, the TF aircraft fuselage width was manually reduced to include a 2-abreast seating arrangement. The fuselage cross-section's height was slightly increased to the same height as the reference fuselage. The sized fuselage cross-section and its cabin parameters are shown in Fig. 23 and Table 11, which feature an elliptical cross-section.

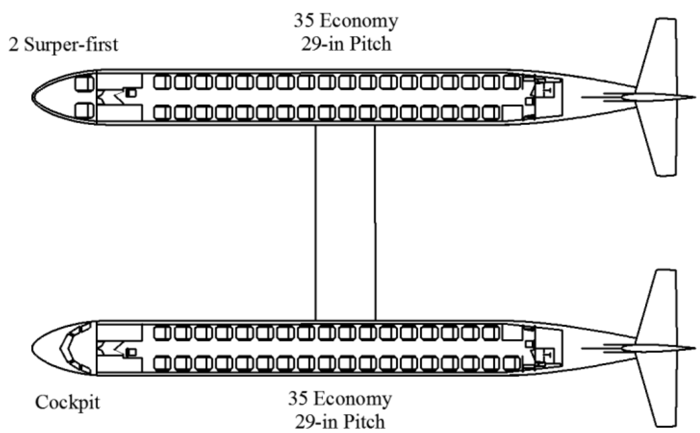

Fig. 22. SR-TF aircraft interior arrangement.

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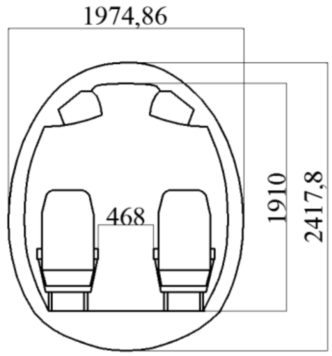

Fig. 23. Fuselage cross-section of SR-TF aircraft.

Table 11 Cabin parameters of SR-TF aircraft

Parameter	SR-TF	ATR 72-600 [39]
Pitch, in	29	29
Seat width, in	18.6	18.6
Aisle width, in	18.4	18.4
Aisle height, in	75.2	75.2
Cabin floor width, in	51.6	89
Floor thickness, in	4	4

2. Aircraft Assessment and Comparison

The flight conditions and aircraft configurations of the SR-SBW and SR-TF aircraft obtained during the initial sizing by PyInit were input into the modified SUAVE for performance analysis through iterative calculations. The SUAVE analysis results of the SR aircraft and the key weight data of the baseline aircraft ATR 72-600 [39] are given in Table 12.

As listed in Table 12, both the SR-SBW and SR-TF configurations with the novel airframe technologies have a significant advantage in fuel efficiency over the reference ATR 72-600 for the proposed short-range mission shown in Fig. 24 (both reduce fuel consumption by more than 20%). However, it is interesting to note that the MTOW, fuel weight, and operating empty weight of the SR-TF aircraft are larger than those of the SR-SBW aircraft, contrary to the MR and LR missions' results. The empty weight breakdown in Table 12 shows that the wing weight of the SR-TF aircraft configuration is still lighter than that of the SR-SBW aircraft, but the weight of the fuselage and the fuselage-related items, including paint and systems, is greater than that of the SR-SBW aircraft, due to the larger fuselage size of the manually modified SR-TF aircraft, which exceeds the wing weight savings.

Table 12 Weight breakdown comparison of RHEA-SR aircraft

Group	SR-SBW	SR-TF	ATR 72-600 [39]
Max. takeoff weight, kg	22229	22945	22800
Fuel weight, kg	1432	1523	2000
Empty weight, kg	12821	13447	13500
Empty weight breakdown			
Wing, kg	2103	1482	
Fuselages, kg	2497	3052	
Propulsion, kg	1019	1047	
Nacelles, kg	269	275	
Landing gear, kg	643	661	

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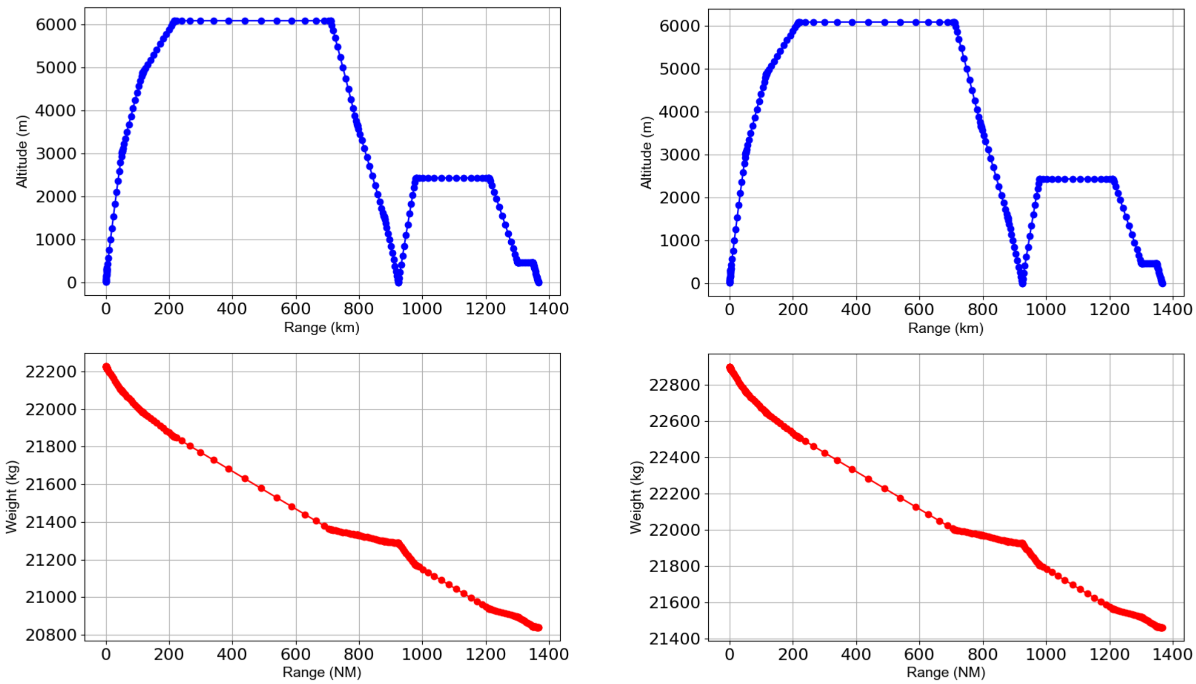
Horizontal tail, kg	201	214
Vertical tail, kg	312	326
Paint, kg	199	240
Systems, kg	5579	6150



a) SR-SBW b) SR-TF

Fig. 24. Mission performance of RHEA-SR aircraft.

As shown in Fig. 25, the geometric dimensions of SR-SBW, SR-TF, and ATR 72-600 are compared. Due to the UHARW design, the RHEA-SR aircraft's wings need to be designed as foldable, as marked in the figure. The SR-TF aircraft fuselage is shorter than that of the SR-SBW aircraft, but it has a slightly larger wingspan due to its higher takeoff weight.

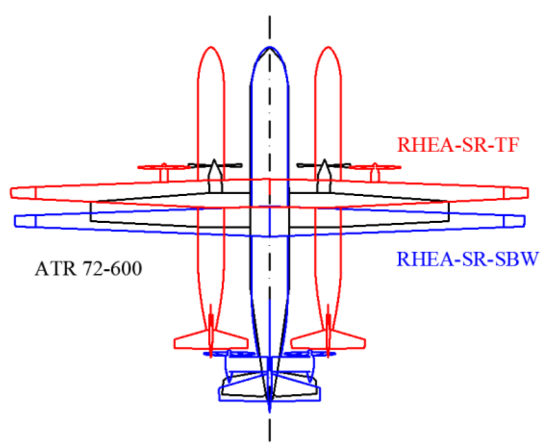


Fig. 25. Geometry comparison of RHEA-SR aircraft.

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Therefore, for the SR mission, the SBW configuration performs better than the TF configuration due to the better fuel efficiency, lighter takeoff weight, smaller wingspan, etc. In future studies, the other TF configurations in Fig. 20 will be compared with the SBW configuration to investigate whether the SBW configuration still has better performance for the SR mission.

In summary, the one SBW configuration and one TF configuration initially proposed for each mission in this section and the final selected one are shown in Fig. 26.

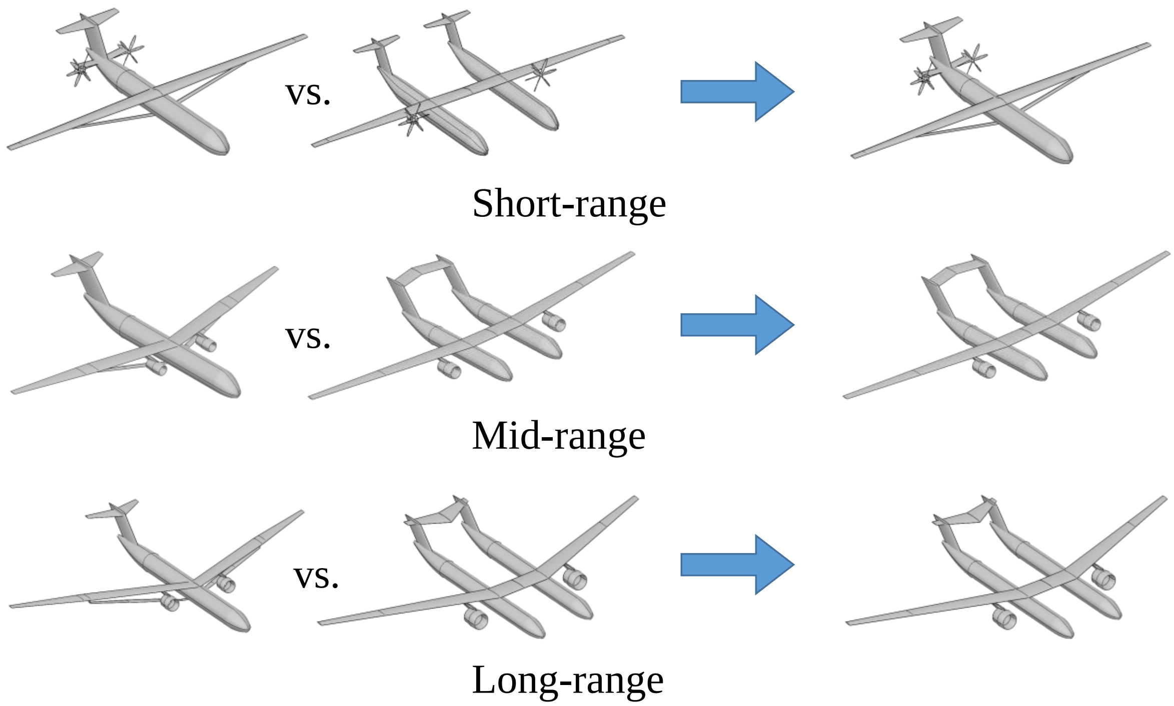

Fig. 26. RHEA aircraft configuration selection process.

V. Conclusion

This paper addressed the conceptual design and comparative study of two unconventional aircraft configurations that facilitate the UHARW design, including the SBW configuration and the TF configuration. Several tools were used in this work for the aircraft conceptual design and performance analysis, which were modified and improved for the SBW and TF configurations and the novel airframe technologies assumed to be available at the EIS framework of the researched aircraft. According to the proposed mission profile and top-level requirements, an SBW and a TF configuration were designed for each mission, respectively, and a comparative study was carried out to determine the best-case configuration for the corresponding mission.

For all three missions researched in this paper (i.e., SR, MR, and LR missions), the TF configuration has a more significant weight reduction effect on the wing weight than that of the SBW configuration, making the MR-TF and LR-TF aircraft perform significantly better than the SBW configuration. However, for the SR mission, considering the specific arrangement of the passenger cabin, the fuselage size had to be adjusted, increasing the total fuselage wetted area and resulting in a higher weight increase of the fuselage and associated systems, thus resulting in the SR-TF aircraft performance inferior to that of the SR-SBW aircraft.

The smaller individual fuselage size of the TF aircraft results in a weaker cargo capacity than that of the SBW configuration. The MR-TF aircraft can barely meet the minimum passenger luggage requirements. While the LR-TF aircraft’s situation is slightly better, it is still far inferior to the conventional and SBW configurations.

There are constraints on the aircraft wingspan and main landing gear span when the aircraft operates at ICAO airports. Due to the TF aircraft characteristics, its fuselage spacing is constrained by the main landing gear span, which brings both new possibilities and restrictions to the TF aircraft’s horizontal tail configuration design. The TF aircraft horizontal tail design requires trade-offs in terms of aerodynamic efficiency, aeroelastic performance, weight, etc. In

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this paper, three completely different horizontal tail configurations were used for the three TF aircraft due to their different operating conditions and fuselage spacing.

This work preliminarily researched the potential of the SBW configuration and TF configuration for the next-generation passenger aircraft with UHARW design. The wing weight estimation methods used in this paper for SBW and TF configurations were Class II and Class II & 1/2, respectively, which have been validated in this paper, and the accuracy is acceptable and feasible for the conceptual design stage. In future work, more accurate wing weight estimation methods will be developed for SBW and TF configurations, and aeroelasticity and flutter analysis will be introduced for UHARW for a detailed comparative study of these two unconventional aircraft configurations. Besides, the configuration comparative research results obtained in this paper were based on the initial conceptual design results. Multidisciplinary design optimization research will be conducted for each concept in the next stage, and then the optimum SBW configuration and TF configuration will be compared again for each mission to study whether the best-case and worst-case configuration will change.

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